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ELECTROMAGNETIC DEEP-PROBING (100-1000 KMS) OF THE EARTH'S INTERIOR FROM ARTIFICIAL SATELLITES: CONSTRAINTS ON THE REGIONAL EMPLACEMENT OF CRUSTAL RESOURCES

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(E82-10155) ELECTROMAGNETIC DEEP-PROBING (100-1000 KMS) OF THE EARTH'S INTERIOR FROM ARTIFICIAL SATELLITES: CONSTRAINTS ON THE REGIONAL EMPLACEMENT OF CRUSTAL RESOURCES Quarterly Progress Report, 30 Sep. - 31 Dec. HC A02/MF A01 G3/43
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John F. Hermance
Department of Geogical Sciences
Brown University
Providence, RI 02912

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Statement of Work

Objective

The objective of this investigation is to evaluate the applicability of electromagnetic deep-sounding experiments using natural sources in the magnetosphere by incorporating Magsat data with other geophysical data.

Approach

The investigator shall pursue the above objective through an analysis of Magsat satellite data, ground-based magnetic observations, appropriate reference field models, and other satellite data.

The objective will be pursued by seeking the optimal combination of observations which lead first to a global, and then to a regional, characterization of the conductivity of the Earth's upper mantle.

Tasks

The following tasks shall be performed by the investigator in fulfillment of the above objective:

a. Use data from Magsat satellite to constrain a long-period global "response function" for the average Earth at low latitudes over a period ranging from 6 hours to 27 days.

b. Synchronize the Magsat data with low-latitude ground-based observatory data to determine the vertical gradient of the respective magnetic field components. Use the vertical gradient of the appropriate components to independently ascertain the separation of external and internal field contributions.

c. Segregate the Magsat electromagnetic "response functions" according to the tectonic regime at the Earth's surface and evaluate systematic differences between regions having lateral scale sizes on the order of 1000 km or greater.

d. Theoretically evaluate problems of resolution and interpretation involving electromagnetic induction by temporally and spatially-varying magnetospheric sources in a rotating inhomogeneous Earth as observed at arbitrary points in space. Use these theoretical studies to constrain the interpretation of Magsat data as well as to propose further applications of satellite-based electromagnetic deep-sounding experiments.

e. Integrate the regional response functions with other geophysical data in order to constrain the joint interpretation of comprehensive physical models.

f. Prepare and submit to NASA periodic progress reports and a detailed final report documenting the results of this investigation.

Electromagnetic Induction and Source Field Effects in MAGSAT Data

A report has been submitted for publication (preprint attached) which uses model simulations to consider two questions: First, are magnetic field effects of induced currents flowing in the earth significant for near-earth satellite observations; Second, what are the effects at satellite altitudes of lateral differences in the gross conductivity structure of the earth. We have found that for distant sources in the magnetosphere, magnetic fields from electric currents induced in a spherical earth may contribute from 30 to 40% of the external source field amplitude. For near-earth sources beneath the satellite, e.g. in the ionsphere, the external and internal fields tend to cancel, resulting in a much smaller total horizontal field than would be associated with sources above the satellite. On the other hand, when lateral differences in conductivity are associated with the contact between major geologic units in the lithosphere, local concentrations of induced current may generate unique magnetic field signatures at satellite altitudes. Although the absolute amplitude of the field components may be an order of magnitude smaller than for the case when the source is above the satellite, the magnetic field perturbation measured by the satellite as it crosses the geologic contact is significantly larger in relative terms for ionspheric sources.

ARE THERE ELECTROMAGNETIC INDUCTION EFFECTS IN MAGSAT DATA? SOME MODEL SIMULATIONS

John F. Hermance

Department of Geological Sciences, Geophysical/Electromagnetics Laboratory
Brown University, Providence, RI 02912

Abstract. This report uses model simulations to consider two questions: first are magnetic field effects of induced currents flowing in the earth significant for near-earth satellite observations; second, what are the effects at satellite altitudes of lateral differences in the gross conductivity structure of the earth. For distant sources in the magnetosphere, magnetic fields from electric currents induced in a spherical earth may contribute from 30 to 40% of the external source field amplitude. For near-earth sources beneath the satellite, e.g. in the ionosphere, the external and internal fields tend to cancel, resulting in a much smaller total horizontal field than would be associated with sources above the satellite. On the other hand, when lateral differences in conductivity are associated with the contact between major geologic units in the lithosphere, local concentrations of induced current may generate unique magnetic field signatures at satellite altitudes. Although the absolute amplitude of the field components may be an order of magnitude smaller than for the case when the source is above the satellite, the magnetic field perturbation measured by the satellite as it crosses the geologic contact is significantly larger in relative terms for ionospheric sources.

Introduction

The earth's magnetic field at MAGSAT altitudes has contributions from the earth's core, static magnetization in the lithosphere, as well as from external electric current systems in the ionosphere and magnetosphere, along with induced electric currents flowing in the conducting earth. The purpose of the following note is to assess the last two of these contributions; the external time-varying fields and their associated internal counter-parts which are electromagnetically induced.

It is readily recognized that during periods of magnetic disturbance, external currents often contribute from 10's to 100's of nanoteslas (gammas) to observations of the earth's field. Since static anomalies from lithospheric magnetization are of this same magnitude or less (Langel et al., 1980), these external source fields must be taken into account when attempting to delineate gross structural features in the crust. What is not so clear, perhaps, is the severity of the effects from the induced field components; this is the issue we wish to address. We will consider two questions: first, are, in fact, induction effects significant for near-earth satellite observations; second, what are the effects of lateral differences in the gross conductivity structure of the earth at satellite altitudes?

Spherical Earth Models

A number of investigations using Sq and Dst variations suggest that on a global scale the solid earth becomes very conducting at depths between 400 and 600 km (Eckhardt et al., 1963; Banks, 1969, Schmucker, 1979). On the other hand, when fluctuations occur such that their depth of penetration in sea water (σ = 3.3 S/m) is on the order of the depth of the ocean (4 km) or less, then appreciable current can be electromagnetically induced directly in the conducting oceans. Induction in the ocean appears to become most efficient at periods of 200 s or less, although certain "ocean-effects" seem to be observed at ground-based magnetic observatories at periods as long as the diurnal variation (24 hr).

To assess global induction effects we assume that, to the first-order, the earth is spherically symmetric and is illuminated by the magnetic field of an equivalent ring current system. Therefore, the source field, B_z^o, is assumed to be uniform and polarized perpendicular to the eclipter plane over the earth's diameter. We adopt the usual spherical coordinate conventions such that in a geocentric coordinate system $\hat{z}$ is directed from the earth's center through the North Pole, θ is colatitude and r is the radial distance. The effects of asymmetries in the ring-current and gradients in the source field are assumed to have second order effects on the result of our discussion.

It is well-known that under these assumptions (e.g. Chapman and Bartels, 1940) the magnetic field relations can be derived from the gradient of a scalar potential ($B = -\nabla U$), where

$$U(r,\theta) = r_o\{I_1(r_o/r)^2 + E_1(r/r_o)\}\cos\theta, \quad (1)$$

I_1 and E_1 are the so-called internal and external potential field coefficients, respectively, r_o, is the radius of the earth, r is the radial position of the observer and θ is the colatitude.

For the purpose of our present discussion we will approximate a region of high conductivity (the oceans at short periods, the upper mantle at longer periods) as a super-conductor ($\sigma = \infty$). The magnetic field component normal to the surface of our super-conductor, $B_r = -\partial U/\partial r$, is zero at r = a. Moreover the external potential for a

uniform source field, B_z^o, is given by
$U = - B_z^o \, r \cos\theta$.

These relations are sufficient to derive the following ratios between the induced field components and the external source field at the satellite altitude, r:

$$B_r^i/B_z^o = -(a/r)^3 \cos\theta, \qquad (2)$$

$$B_\theta^i/B_z^o = -0.5 \, (a/r)^3 \sin\theta. \qquad (3)$$

It is clear that, for a satellite at a nominal altitude of 400 km and a highly-conducting mantle at a depth of 400 km, one has an induced contribution of on the order of 34% of the external field. Since, for example, during the recovery phase of a magnetic storm Dst may have magnitudes of 100 gammas or larger, one may have long-term induced fields which are several tens of gammas in magnitude; larger in fact at satellite altitudes than the static fields from most lithospheric magnetic anomalies (Langel et al., 1980).

At shorter periods (200 s to 1 hr), the satellite would see the conducting oceans as a super conductor at the earth's surface. In this case the induced contribution at satellite altitudes might be as much as 42% of the source field. One can, in fact, see from relations (2) and (3) that one might want to consider induction effects at satellite altitudes less than 2 earth radii (at L=2, $B_z/B_z \sim 6.25\%$). Beyond this distance the dipolar character of the induced field precludes significant contributions from induction effects in the earth.

Induction in a Plane-Layered Earth

Having argued that significant induction fields are present at MAGSAT altitude we can address some details regarding the nature of these fields, namely how do they differ for sources above the satellite in the magnetosphere or below the satellite in the ionosphere? In addition, what are the effects on satellite observations of gross lateral conductivity variations within the earth?

It is often appropriate and useful to represent the conductivity structure of the spherical earth by a medium in which the electrical properties vary only in the vertical (or radial) direction. Moreover when characteristic scale lengths of particular phenomena (e.g. depths of penetration, source field dimensions, satellite heights, etc.) are small compared with the earth's radius, r_o, it also becomes appropriate to represent the earth as a plane-layered medium having a flat, horizontal surface extending to infinity in all directions.

Under these conditions, for a conventional geomagnetic coordinate system at the earth's surface ($\hat{x}$, $\hat{y}$ horizontal, $\hat{z}$ positive downward), one can show quite readily (e.g. Hermance and Peltier, 1970) that an equivalent two-dimensional current sheet source at a height $z = -h$, having a characteristic wavenumber $k = 2\pi/\lambda$ (λ being the spatial wavelength), generates a horizontal magnetic flux density of the form

$$B_x^o = (\mu I/2) \exp\,[-k(z+h)]\, \exp\,(-ikx) \qquad (4)$$

when seen below the source, and of the form

$$B_x^o = -(\mu I/2) \exp\,[k(z+h)]\, \exp\,(-ikx) \qquad (5)$$

when seen above the source. In these and our subsequent expressions $\underline{B}$ is in nanoteslas (gammas), I is the amplitude of the source current density (A/m), and $k=2\pi/\lambda$ is the wave number.

Electric currents are induced in the finitely conducting earth and generate secondary magnetic fields which can be represented in the form

$$B_x = (\mu I/2)\, R \exp\,[k(z-h)]\, \exp\,(-ikx) \qquad (6)$$

throughout the space above the earth, both below and above the source. The term R is a complex reflection coefficient ($|R| \leq 1.0$) dependent on k and the internal conductivity structure of the earth. In general $R = (Z_o - Z_s)/(Z_o + Z_s)$, where $Z_o = i\omega\mu/k$ is the generalized impedance of free space at wavenumber k, (in the case where the spatial wavelength is much smaller than the free space wavelength) and Z_s is the generalized surface impedance of the layered earth, also at wavenumber k.

Generally, global estimates of apparent resistivity (ρ_a) at periods of 3 hours, or somewhat longer, fall within a range of 10 to 100 ohm-m, or have a geometric mean of 30 ohm-m. This would correspond to a surface impedance at 10,800 s (3 hr) of $|Z_s| = (\omega\mu\rho_a)^{\frac{1}{2}}$, or $1.5 \cdot 10^{-4}$ ohms. In contrast, $|Z_o| = |\omega\mu/k|$ or $2.3 \cdot 10^{-3}$ ohms. Clearly $|Z_s| << |Z_o|$ for reasonable geophysical situations, so that the reflection coefficient can be rewritten using a binomial expansion in the approximate form $R \sim 1 - 2(Z_s/Z_o)$, where the magnitude of the second term on the right hand side is 0.13. Hence, approximately 87% of the incident electromagnetic energy is reflected from the earth's surface.

For distant sources in the magnetosphere (i.e. sources above the satellite) it is clear that the total horizontal field component seen at satellite altitudes (the sum of (4) and (6)) is quite close to twice the source field strength. On the other hand, when the source is beneath the satellite, the total horizontal field component (the sum of (5) and (6)) is on the order of a percent, more or less. Differential geometrical spreading due to the exponential attenuation of the source and "image" fields will modify these results somewhat, as will a smaller spatial wavelength than that considered above. Both effects will tend to make B_x (total) larger when the equivalent current source is beneath the satellite. The primary point we wish to make however is that for our plane-earth model there is a tendency for B_x (total) to be twice the amplitude of the source field when sources are above the satellite (i.e. in the magnetosphere), and a tendency for B_x (total) to be reduced to zero when sources are beneath the satellite (i.e. in the ionosphere). Both of these results follow intuitively from a simple consideration of Lenz's law and the right hand rule.

Induction in a Laterally Heterogeneous Earth

We now consider induction effects for the situation illustrated in Figure 1. A satellite, at a nominal altitude of 400 km, passes over an ionospheric current system (at a height of 110 km), along a path which crosses a major geologic contact separating materials having a resistivity contrast of a factor of 2, not untypical of differences in gross continental lithologies. Although in many cases, resistivity contrasts may be much larger, particularly at a continent-ocean interface, this model, while conservative, is sufficient to illustrate the effects we wish to discuss.

To consider this problem quantitatively, a numerical algorithm has been developed by our group. At this stage we represent the surface of the earth by an infinite horizontal plane and consider only two-dimensional heterogeneities. Although our numerical model can handle more complicated geologic structures, here we consider only the case of a vertical contact separating two quarter-spaces having different resistivities; 30 ohm-m and 15 ohm-m, respectively. Typical results from our model simulation for ionospheric currents flowing parallel to a representative geologic discontinuity are shown in Figure 2. The magnetic field component B_x, measured in the direction of the satellite trajectory, is plotted for various situations.

The topmost curve represents the total horizontal field component at the earth's surface for a uniform or an infinite plane wave source which might be associated with distant magnetospheric current systems. Directly beneath the uniform source curve, we show B_x (total) at the earth's surface for the finite source ($\lambda=2\cdot10^4$km). The overall amplitude of B_x (total) for the finite source is reduced somewhat because of the exponential geometrical spreading factor; however the amplitude of the local anomaly associated with the geologic contact is approximately the same. B_x (total) for the finite source decreases to either side of the contact (at distances greater than 1000 km) because of the curvature of the source field.

The third curve from the top in Figure 2 represents the amplitude of the source field alone when seen by an observer directly below it. The bottom-most curve represents B_x (total) as seen at satellite altitudes (400 km), when

the current source is in the ionosphere (110 km). The sign of this field is negative relative to the other fields plotted in this figure, but it is shown on the same graph for comparison. Although B_x (total) at the satellite altitude is an order of magnitude smaller than at the earth's surface (because of cancellation effects from the source current as discussed above) the anomalous behavior of the satellite observations as the vehicle passes over the geologic contact is relatively more pronounced.

We have calculated, although not shown, B_x (total) at satellite altitudes for a uniform field from magnetospheric sources above the satellite. It has an amplitude of approximately unity relative to the results simulated in Figure 2. At -500 km it has a minimum of 0.98 nT and at +400 km it has a maximum of 1.01 nT. This 0.03 nT peak to peak difference in amplitude at satellite altitude is significantly smaller than the ground-based amplitude of 0.12 nT because of the exponential geometric spreading factor. It is evident that a satellite anomaly having a spatial wavelength of 1,800 km (2 times the distance between the minimum and maximum amplitudes) would be larger at the earth's surface by a factor of $\exp(2\pi \cdot 400/1800)$, approximately a factor of 4.

The gross features of the induced anomaly itself do not differ substantially for a uniform source field or for a finite source field. What is most important is the position of the source itself, that is to say whether it is above or below the satellite. Although the 0.03 nT fluctuation in the satellite observations would not be discernible from unity in Figure 2 when the source field is above the satellite, it is quite noticeable in the case where the source is below the satellite. This, of course, is due to the nulling effect of the internal and external horizontal fields that was discussed above.

The results summarized in Figure 2 are for a source field having an amplitude of 0.5 nT. When the total disturbance field is B_x = 100 nT at the earth's surface and is due primarily to ionospheric current systems, B_x at satellite altitudes would have a magnitude on the order of 5 nT, well within the resolution of MAGSAT data. Moreover a well-defined (1000 km wide) maximum in the horizontal gradient of B_x would be associated with such an electrical discontinuity. It seems possible therefore that the

investigation of the lithosphere in terms of its gross electrical properties might serve as a useful complement to studies of its large-scale magnetization properties.

Conclusions

We have shown that induction in a spherical earth by distant magnetospheric sources can contribute magnetic field fluctuations at MAGSAT altitudes which are 30% to 40% of the external field amplitudes. When the characteristic dimensions (e.g. depth of penetration, etc.) of a particular situation are small compared with the earth's radius, the earth can be approximated by a plane horizontal half-space. In this case electromagnetic energy is reflected with close to 100% efficiency from the earth's surface. This implies that the total horizontal field B_x is twice the source field when the source is above the satellite, but is reduced to values which are much smaller than the source field when the source is below the satellite. This latter effect tends to enhance the signature of gross electrical discontinuities in the lithosphere when observed at satellite altitudes.

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Fig. 1. Schematic of physical situation simulated by our model. A satellite passing above an ionospheric current source crosses a geologic contact between major lithologic units (ρ = 30Ω-m and 15Ω-m, respectively).

Fig. 2. The magnetic field component (B_x) parallel to the direction of the satellite trajectory. From top to bottom: B_x (total) at the earth's surface for uniform and for finite source fields; the field of the finite source alone when seen from directly below; B_x (total) at satellite altitudes (400 km) when the finite source is in the ionosphere below (110 km). The appropriate scale sign is denoted by (+) or (-). Period = 10,800 s.

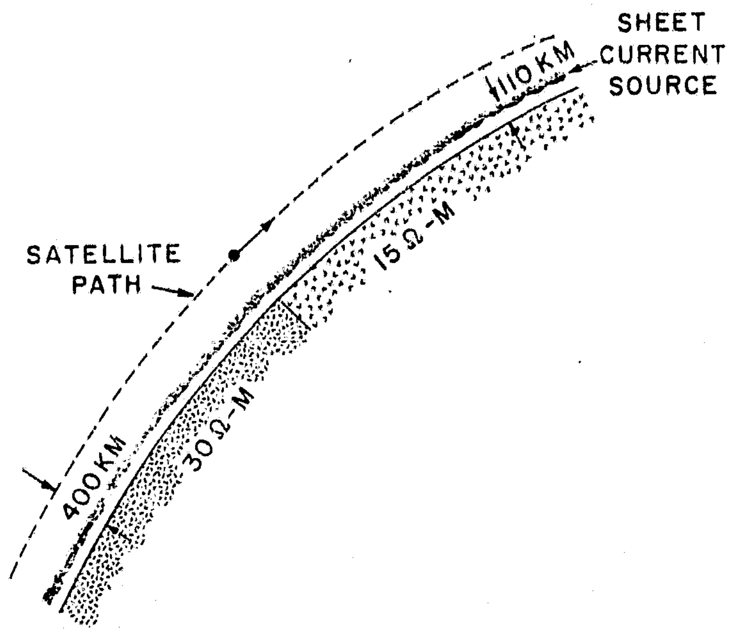

FIGURE 1

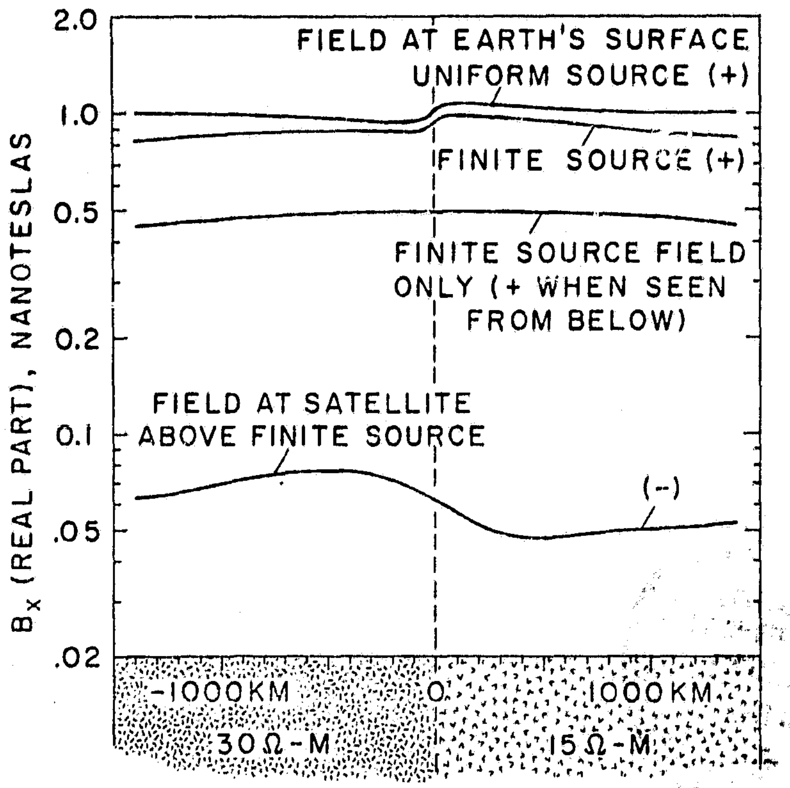
2.0
1.0
0.5
0.2
0.1
.05
.02
FIELD AT EARTH'S SURFACE
UNIFORM SOURCE (+)
FINITE SOURCE (+)
FINITE SOURCE FIELD
ONLY (+ WHEN SEEN
FROM BELOW)
FIELD AT SATELLITE
ABOVE FINITE SOURCE
(-)
B_X (REAL PART), NANOTESLAS
-1000KM
0
1000KM
30 Ω-M
15 Ω-M

FIGURE 2